IEA/H2/T11/FR1-2000

INTERNATIONAL ENERGY AGENCY
HYDROGEN IMPLEMENTING AGREEMENT
TASK 11: INTEGRATED SYSTEMS

Final report of Subtask A:
Case Studies of
Integrated Hydrogen Energy Systems

Chapter 8 of 11

T. Schucan
Paul Scherrer Institute
Switzerland

Chapter 8
SAPHYS: STAND-ALONE SMALL SIZE PHOTOVOLTAIC HYDROGEN ENERGY SYSTEM

1. PROJECT GOALS

The Stand-Alone Small Size Photovoltaic HYdrogen Energy System (SAPHYS) Project was a joint project of ENEA (Ente per le Nuove Tecnologie, l'Energia e l'Ambiente; Italy), IFE (Institutt for Energiteknikk; Norway), and KFA (Forschungszentrum Jülich, Germany), and was supported by the European Commission within the framework of the Non-Nuclear Energy Programme Joule-II. The purpose of the program was to address issues related to global environmental problems caused by the use of fossil fuels, giving rise to changes in global climate. A more extensive use of renewable energy and an industrial transition from a petroleum economy to a non-fossil fuel economy such as hydrogen, could help resolve these problems. SAPHYS was conceived to test and demonstrate safe and effective long-term storage of hydrogen produced by renewable energy using solar powered electrolysis of water, and to regenerate the stored energy into electric energy with a fuel cell.

The objectives of the project were:

- to assess the efficiency of hydrogen used as a storage medium of solar electric energy, and
- to design and test a small SAPHYS system for unattended operation.

2. GENERAL DESCRIPTION OF PROJECT

Even if better performance and operation of plant could be obtained at larger scale, the scope of this demonstration suggested a reduced size plant. SAPHYS plants (of several kWs in size) are proposed for remote and isolated applications such as telecommunication energy systems, isolated houses on small islands, or a remote environmental monitoring station. Such applications could then represent an initial market niche for solar-hydrogen technology.

The system consists of a photovoltaic array that supplies energy to a variable simulated load, backed by battery storage for short-term energy fluctuations. Excess energy from the photovoltaic array is utilized for the production of hydrogen by electrolysis of water. A proton exchange membrane (PEM) fuel cell is included for production of electricity when the solar input is not sufficient and the batteries are nearly completely discharged. The system was designed to operate in a stand-alone (fully automated) mode, with appropriate computer controls and data acquisition.

The construction project lasted 36 months, from July 1994 through June 1997. Automatic operation commenced in September 1997.

3. DESCRIPTION OF COMPONENTS

Most of the components of the system have been assembled at the ENEA Research Centre in Casaccia (near Rome) using the Photovoltaic Hydrogen Test Rig (PHYTR). The two major improvements within the SAPHYS project were the replacement of the electrolyzer stack with an advanced one, and the implementation of an integrated plant control system.

3.1 Photovoltaic Hydrogen Test Rig

The PV array consists of 180 single crystalline modules produced by different manufacturers (Arcosolar, Helios and Italsolar), configured into 8 sub-arrays. The inclination of 50° was chosen in order to increase the winter energy production. All sub-arrays were wired for a nominal 36 V_{DC} operation and 60 V_{DC} open circuit voltage with a rated power of 5.6 kW at nominal conditions (1000 W/m^2; 25°C). Each array is connected directly to the bus bar.

The lead acid battery has a storage capacity of 51 kW, configured as 34 V_{DC}, (1500 Ah).

The hydrogen storage capacity was designed to be at least 300 Nm^3, but the actual capacity is somewhat less. As a consequence, the time of a continuous winter test will be limited. The maximum storage pressure was about 20 bar.

An electronic load is used to simulate the energy/power demand of two isolated houses with typical domestic electric and electronic devices. The summer load profile is characterized by small and short hourly peaks of about 0.4 kW and two high consumption peaks (4 kW in the morning and 2.5 kW in the evening). The daily energy consumption during summer test was 11 kWh.

Ancillary equipment (compressed air, heating/cooling, hydrogen drying and purification, process water treatment, inert gas, electric devices, etc.) and monitoring and control systems were directly powered by the grid, and their energy demand was calculated for the net plant efficiency evaluation.

3.2 Electrolyzer

The electrolyzer section consists of a Metkon-Alyzer Model 0100 electrolyzer unit framework assembled with advanced cells specifically designed and manufactured by KFA for solar application, capable of operating up to 20 bar.

Apart from high energy efficiency and good dynamic performance in intermittent operation, a particularly important requirement for solar-operated water electrolyzer is the possibility of operating the electrolyzer over a wide range with high current yields and sufficient gas purities. To match the actual plant power, the existing electrolyzer of 2.5 kW was revamped for 5 kW, the required power according to the design data specified from simulations. This was done in co-operation with Casale Chemicals S.A. Furthermore, the electrolyzer control was modified to ensure fully automatic operation within the SAPHYS system.

With the aid of the SIMWELLY simulation program, developed at the Research Centre Jülich for design and optimization of alkaline bipolar electrolyzer, the 5 kW pressurized electrolyzer was designed and its performance data evaluated. This included calculation of the current/voltage curves, bypass currents, current yield, energy yield and overall efficiency for a temperature range of 25-80°C. The electrolyzer stack, similarly to the old stack, consists of 17 cells, connected in a bipolar configuration, with a single-electrode surface of 600 cm^2. An overall efficiency of approximately 87% (HHV) was calculated at 80°C and a rated power of 5 kW. This high level of efficiency for a technically advanced electrolyzer was achieved by using state-of-the-art electrodes and diaphragms. The electrode activation must be protected against corrosion by a minimum polarization voltage during electrolyzer down times (1.3 V/cell). Some of the technical characteristics of the advanced electrolyzer module are summarized in Table 8.1.

Table 8.1: Technical characteristics of advanced electrolyzer module

Peak power	5 kW
Cell active surface	6 dm^2
Stack cells	17
Electrolyte concentration	30% KOH
Operating temperature	80°C
Operating pressure	20 bar (max.)
Current[1]	180 A
Cell voltage[2]	1.67 V_{DC}
Module voltage[2]	28.4 V_{DC}
Heat to be removed[1]	580 W
Cell frame materials	PSU 5% G
Electrode materials	activated nickel
Diaphragm	NiO
Bipolar frame	Nickel

1) at peak power
2) at peak power and 80°C

3.3 Fuel Cell

The fuel cell is a Ballard Power Generator System (PGS) 103A solid polymer fuel cell (SPFC) electrical generator. It is rated at 3 kW_{DC} power, with air as oxidant, and it was designed mainly for demonstration and evaluation. Its main features are: the capability to operate at low temperature (about 72°C); its short start-up period; no significant stand-by problems; its simple installation and operation; its quick response to load changes; and its high efficiency.

The PGS, as supplied, includes hydrogen circulation, water circulation and cooling management, temperature control, and a number of additional controls and monitoring devices. It is configured to operate as a stand-alone unit for hydrogen pressures up to 30 psig (3.1 bar) and air system pressures to a maximum of 50 psig (4.4 bar). The system has a limited operating range due to its configuration as a demonstration unit and the design limitations of some of the system components. Its main characteristics are summarized in Table 8.2 and a top view is shown in Picture 8.1.

Table 8.2: System specifications of Ballard fuel cell

System designation	PGS 103 A
Stack cells	35
Electrolyte	Nafion 117
Plate material	Graphite
Active electrode area	232 cm^2
Cooling cells	19
Humidification cells	14
Stack dimensions	49x25x25 cm
PGS dimensions	104x80x37 cm
Stack weight	43 kg
PGS weight	150 kg
Fuel	Hydrogen
Oxidant	oxygen or air
Performance[1]	>21 V_{DC} at 125 A
Rated power (with air)	3000 W
Support system power	<250 W

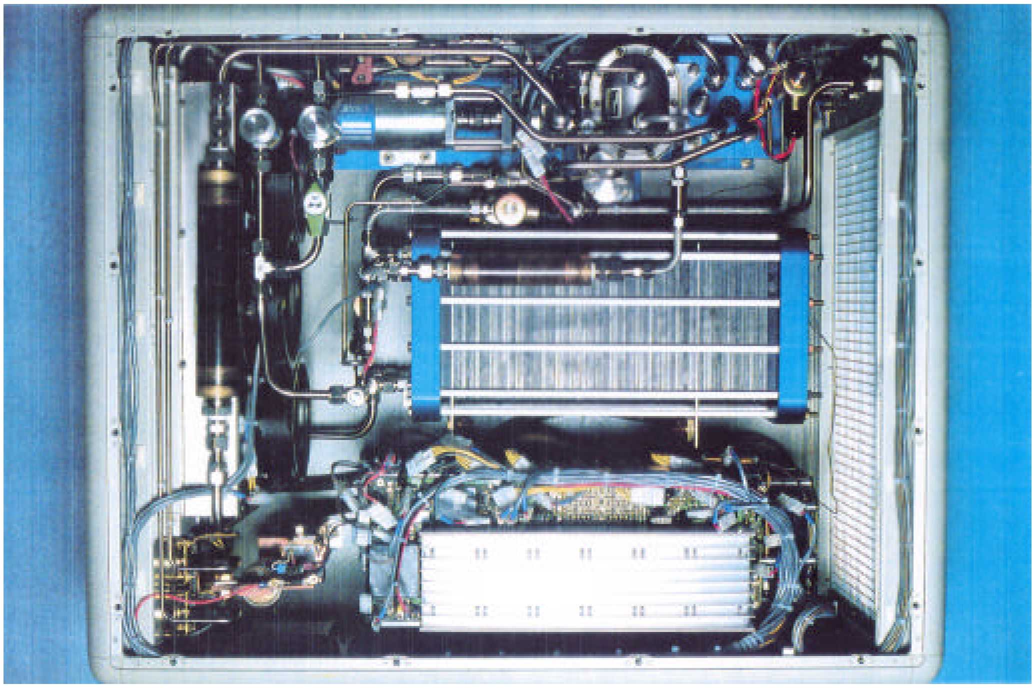
1) at 30 psig H_2/air at 70°C

3.4 Control system

The control system of the SAPHYS plant consists of three separate parts hierarchically organized. These parts are:

- the control systems for the electrolyzer, the fuel cell, and the hydrogen circuit
- the Alarm and Supervision Board (ASB)
- the Master Control System (MCS) performing energy management (EM)

The objective for the MCS is to control the electrolyzer and the fuel cell operation. The outputs from the MCS are the set-points for the currents to the electrolyzer and for the fuel cell DC-DC converters, and digital signals for starting and stopping the electrolyzer, the fuel cell, and related ancillary equipment in a controlled sequence. With the EM algorithm, these outputs are manipulated according to the state of charge (SOC) of the battery, which is estimated by the measurements of battery voltage, current, and temperature. Two methods were developed for battery SOC estimation: simplified (based on the algebraic sum of battery currents); and advanced (including a gassing current model).



Picture 8.1: Top view of the Fuel Cell Power Generator PGS-103 (photo provided by courtesy of Ballard Power Systems Inc.)

4. SIMULATION

In order to perform the SAPHYS system analysis and design, and to develop a control strategy for the system EM, the models of the plant components including insolation and load profiles were built and implemented in the Jülich simulation system, JULSIM program. JULSIM was developed by KFA for their solar-hydrogen plant, PHOEBUS. The EM rationale, based on the control of the SOC of the battery, was developed and optimized for high plant energy efficiency as well as for careful battery operation. Some parts of the code were to be implemented in the actual control system of the plant. The characteristics of the EM are:

- A so-called "five-state-controller" minimizes the use of the low-efficiency gas storage system. Its switching hysteresis minimizes the losses and wear of the electrolyzer and the fuel cell.
- The electrolyzer and the fuel cell are operated in such a way that the battery charge throughput is minimized.

After simulation and evaluation of many annual scenarios, optimized results were used as input for the plant design.

5. INTEGRATION OF COMPONENTS

The integration of components was a major part of the study undertaken for the SAPHYS Project, including:

- the development of a plant modeling program to determine the efficient component integration and basic control logic according to the solar input energy and the user power requirement
- the design, manufacturing and installation of new equipment necessary to implement the stand-alone unattended plant, with particular emphasis on an advanced electrolyzer stack specifically designed for solar application
- the design of a control system (MCS) to implement the basic control logic for unattended operation and energy management
- the modifications on the existing PHYTR (Photovoltaic Hydrogen Test Rig) at ENEA Casaccia Research Centre according to the new SAPHYS design
- experimental testing of the SAPHYS plant and of the MCS
- analysis of results and evaluation.

The PV array supplied energy to the load by a common electric bus bar. A battery storage unit continuously connected to the bus bar stabilized line voltage and compensated for short-term excess or deficit energy from the PV arrays. According to the SOC of battery storage, the MCS activated the electrolyzer or the fuel cell, according to EM rationale. Both pieces of equipment were connected by two separate DC-DC converters controlled by the MCS as well.

6. OPERATIONAL EXPERIENCE

After completion of the plant in the spring of 1997, some continuous test runs were performed to check the actual operation of SAPHYS. The tests identified some problems that were analyzed and almost completely solved. A set of tests was performed to check the correct communication and operation of the programmable logic controller (PLC) with the plant. Some adjustments on the MCS parameters were required to adapt the control system to actual plant dynamics. The loop time for performing the decisions to start and stop equipment and to define the DC-DC current set points was set to 1 minute. This time appeared to be adequate for prompt control action and plant stability.

Analysis of early tests showed a mismatch in the daily algebraic sum of the currents at the bus bar. However, less than the maximum calculated error occurred according to the actual instrument accuracy (1%). The error, due to the harmonic interference between DC-DC converter operation and battery current transducer, was solved by filtering the input signal to the transmitter.

On September 2, 1997, long-term continuous testing began in a fully automatic mode 24 hours a day, seven days a week. Due to the sunny weather of the first test period (two months), data acquired can be considered representative only of the summer operation of SAPHYS. Minor faults in some of the ancillary equipment (demineralization unit, air compression system, and PLC board) caused some short plant stops.

Concerning the implementation of the demonstration system at the ENEA Casaccia Research Centre, the following observations can be made:

- As built, the plant is very complex, and the presence of many components increases parasitic energy consumption and could reduce plant reliability.

- Electrolyzer technology appears to be mature enough for solar application. On the other hand, the electrochemical effects of operation for periods with an intermittent power source and consequent deterioration of yields with time has to be tested.
- The SAPHYS configuration with DC-DC converters separated the electrolyzer from fast voltage fluctuations at the bus-bar level. It does, however, introduce further inefficiencies. The presence of the battery produces a smooth current profile to the electrolyzer, even during temporary periods of low or irregular insolation.
- Although the electrolyzer was demonstrated to be reliable and its operation satisfactory, the same was not true for the auxiliary equipment required for its operation (water demineralization unit, compressed air treatment unit, and inert gas). Due to the small plant size, the equipment has to be simple in order to limit the cost and energy consumption. Faults in auxiliaries operation were the main cause of plant stops.
- The solid polymer fuel cell is suitable for a small-scale system. However, this type of fuel cell can suffer from long stand-by periods and from freezing temperatures. Maintenance should be provided at least once before the wintertime.
- The SAPHYS control system was demonstrated to be appropriate for the plant features. Even if the PLC RTU-210 has a fault, it can be considered a substantially reliable technological approach for SAPHYS control.
- The use of DC-DC converters and a "five state controller," using SOC as the variable to operate the electrolyzer and fuel cell, allows for smooth equipment operation, and in the case of the electrolyzer, a high-current operation with high grade purity hydrogen production. Plant control and operation is more flexible and can be easily optimized. Voltages during operation were found to be more sensitive to load variation and SAPHYS controls, based on bus-bar voltage, rather than on the SOC, which would have been more troublesome. On the other hand SOC, as calculated by the MCS, is very sensitive to current measurement, and discrepancies with actual energy stored in the battery occurs even when a small error in measurement is present. A very accurate measurement and an automatic (or manual) periodic check and reset of the actual SOC were then introduced in the MCS.

7. PERFORMANCE

During the two-month test period between 2 September to 3 November 1997, the system operated for about 1200 hours. Due to the sunny weather during this first test period, the PV array was available to supply energy to the simulated load, and to produce hydrogen; there was no need to use hydrogen to run the fuel cell. Thus, only the performance of the electrolyzer and related DC-DC converter were determined. No year-round plant performance could be evaluated because of the need to obtain experimental data from the energy regeneration section (fuel cell and up-converter).

In general, both electrolyzer and plant efficiencies were very encouraging and compare well with those obtained in similar experiences. The PV array provided a little over one third of its energy to the load (439 kWh) and two thirds to the electrolyzer to make hydrogen (768 kWh). A total of 123 Nm^3 of hydrogen were produced during this two-month period.

The daily behavior of plant operation and performance for a typical sunny day (22 October 1997) is displayed in Figure 8.1.

The lower trace shows the battery SOC course as calculated in the MCS. After a small decrease of battery charge from midnight to about 8:00, there is a continuos charge of battery from that minimum SOC value (77%) due to the solar energy input (upper trace in figure).

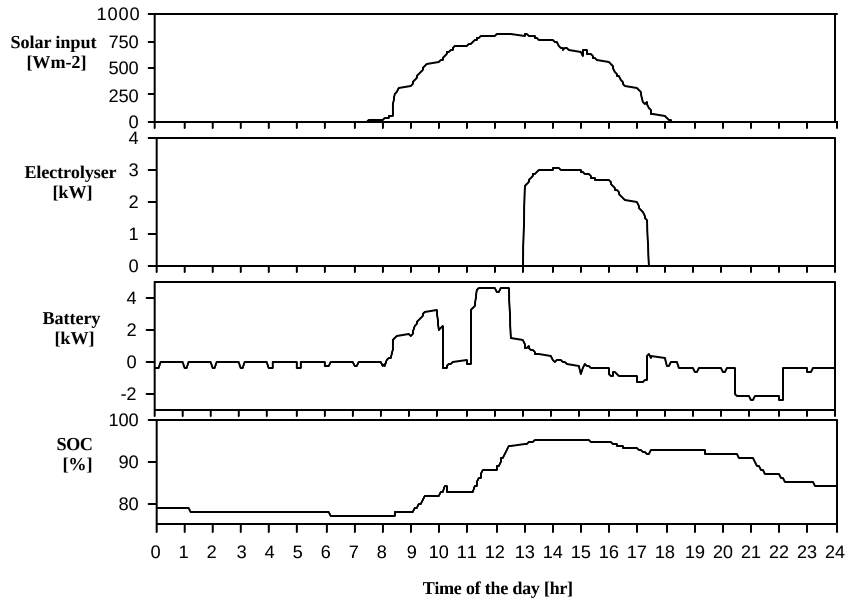


Figure 8.1: Experimental data for a typical sunny day (22 October 1997)

After midday, the SOC reaches the value for starting up the electrolyzer (94%). For the high value of current to electrolyzer, the hydrogen produced has a high grade of purity.

After electrolyzer start-up, the PV array supplies energy both to the electrolyzer and battery. As a consequence of the SOC changes, and according to the SOC-electrolyzer current relationship, the current supplied to the electrolyzer is changed as well. At about 17:30 the electrolyzer is stopped for low current from PV array and from now on, the load is powered by the battery.

The maximum electrolyzer temperature on this day was just over 50°C. The temperature set-point (80°C) for electrolyte external cooling was never reached during the overall test period.

Regarding the load, it can be noticed that the first high power demand (in the morning) is supplied almost completely by the PV array, while the evening peak is provided by the battery alone.

A further behavior is represented by days with significant dynamics that represent the most critical tests for both control system and components of plant (Figure 8.2). In this case (4 September 1997), even with a variable solar input, the use of SOC as a control variable smoothes the signal of set-point of the current to be sent to electrolyzer: The buffer function of the battery in this condition is evident.

The daily average efficiencies of the electrolyzer appear just a little lower than the simulation values (77.4%), but with an average operating temperature in the electrolyzer always below the design value. The cumulative distributions of Faraday, voltage, and electrolyzer efficiencies are shown in Figure 8.3. These values appear encouraging considering, the low operating temperature and taking into account the energy losses for hydrogen flushing at start-up and shut-down and for protective current in stand-by operation. On the other hand, the down converter had an average efficiency of 76.6%, well below the forecast value used during the simulation. The overall efficiency of the hydrogen production section (down converter, cable resistive losses and electrolyzer) was 54.7%.

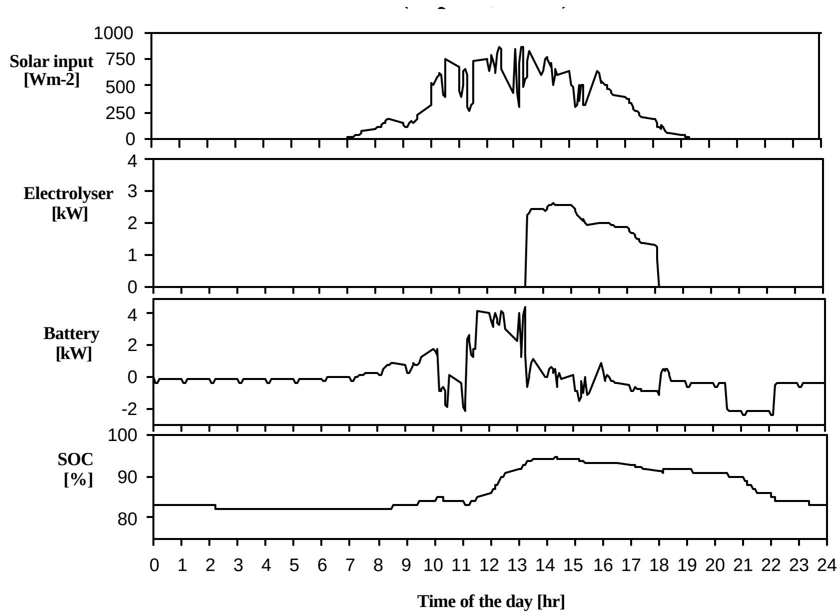


Figure 8.2: Experimental data for a cloudy day (4 September 1997)

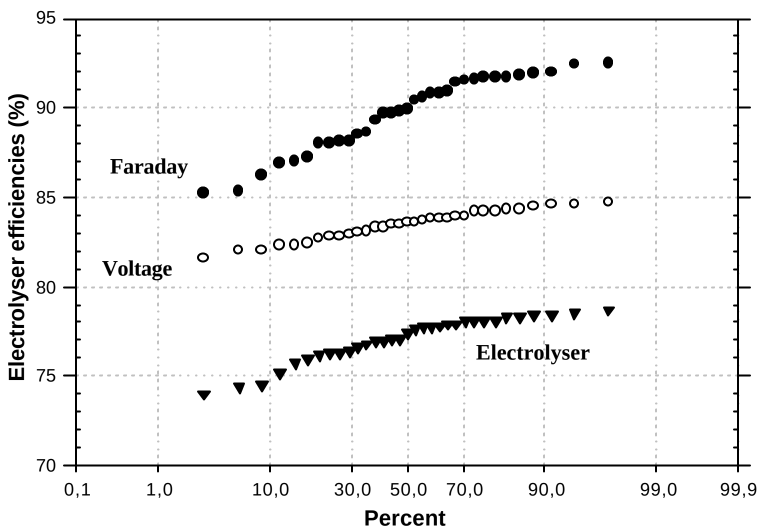


Figure 8.3: Cumulative distributions of electrolyzer efficiencies (2 September - 3 November 1997)

The PV and solar system efficiencies are considered as the ratio of the sum of used energy for supplying load and hydrogen stored energy to either PV or solar input energy. The PV systems efficiency is 71.1% and the solar system efficiency is 5.0%. The latter system efficiency is low mainly as a result of the aged modules of the PV array (about 20 years old) and their obsolete technology.

8. FUTURE PLANS

As a result of the SAPHYS project, it was found that the overall performance and operation of such a system could be improved by adopting some design guidelines such as:

- The operating bus-bar voltage should be increased so as to reduce current (and cable section area).
- As many "off-the-shelf" electric items (switch, fuse, DC-DC converter) as possible should be used.
- The plant should be compact, so as to reduce cabling and electric losses between equipment.
- The measurement accuracy of the currents to and from the battery for SOC calculations in the MCS should be increased.
- A single DC-DC converter for both electrolyzer and fuel cell connection should be used if the SAPHYS configuration with the DC-DC converters is adopted.
- A major breakthrough would occur if a single, reversible piece of equipment performing both electrolyzer and fuel cell operations could be developed.
- The balance-of-system components should be minimized to decrease passive energy consumption and increase plant reliability.
- Considering the fact that the plant is located remotely, and is operated in an unmanned mode, the number of alarm and monitoring circuits could be minimized without compromising safety.
- A six-month scheduled maintenance should be sufficient for a well-designed SAPHYS.

At the beginning of the project, it was planned that the SAPHYS experimentation would be carried out for at least one year. Some equipment and control systems had to be tested in wintertime and their performance compared with the forecast data used during the design phase. Tests were to be performed according to the test plan and be mainly aimed to check up on the control system, system performance, and thermal and electrochemical equipment behavior. Post-test analysis and evaluation were to be conducted to determine how various components have been affected by the demonstration.

In particular, the following aspects were to be investigated:

Fuel cell:

The energy regeneration phase, during which stored hydrogen is converted into electric energy, has to be tested.

Hydrogen purification section:

The performance of the hydrogen dryer and de-oxidation unit just after the electrolyzer has to be thoroughly tested with the installation of further analytical instruments.

SOC calculations:

The advanced SOC calculation method (with gassing current) in energy management has to be used and checked against the present simplified method (that sums battery current algebraically to update SOC). Better methods have to be developed to avoid discrepancy between the calculated and the actual SOC value.

MSC improvements:

An adaptive algorithm is needed to determine whether variable SOC limits, according to external conditions (e.g. weather conditions), could be implemented in MCS.

Electrolyzer current set-point calculation in EM:

Presently the set point of the current to be supplied through the down converter to the electrolyzer is calculated proportionally to SOC. An alternative method is possible: The current can be adjusted to continuously compensate for the battery current, summing up or subtracting the previous battery current value from the previous down-converter current set-point. This method should be faster than the present one and should reduce the high current flow between the battery and electrolyzer during the start-up of the latter.

Overall plant performance:

After operation of all the sections of the plant it will finally be possible to evaluate the performance of the overall plant against the estimated value in the design phase. The actual energy consumption of the auxiliary components and devices should be determined and added to the simulated load to obtain the actual efficiency of a stand-alone photovoltaic hydrogen energy system.

Comparison of experimental data with simulation:

Using the JULSIM simulation code, the output of simulation runs will be compared with experimental data from the plant, and model parameters will be adjusted accordingly.

Due to the fact that there are no more funds and no supporting program available for the SAPHYS project, the plans to record performance and gain experience in the energy regeneration section (fuel cell and up-converter) in an all-year-round plant operation will have to be continued on a voluntary basis. Unfortunately, continuous runs over longer periods of time will not be possible with these boundary conditions.

9. CONCLUSIONS

From the experience with this project, it may be concluded that there are no insurmountable technical problems associated with hydrogen production by PV-powered electrolyzer. Field observations show that PV-H_2 systems are feasible and reliable enough, and require limited maintenance.

Electrolyzer technology appears to be mature enough for solar application. On the other hand, the electrochemical effects of operation for periods with an intermittent power source and consequent deterioration of yields with time has to be tested.

Although the electrolyzer was demonstrated to be reliable and its operation satisfactory, the same was not true for the auxiliary equipment required for its operation (water demineralization unit, compressed air treatment unit, and inert gas). Due to the small plant size, the equipment has to be simple in order to limit the cost and energy consumption. Faults in auxiliary operations were the main cause of plant stops.

The adoption of a straightforward configuration (e.g. one pressurized, reversible electrolyzer/ fuel cell unit without a purification section and directly connected to the bus bar, a cheap gas holder for hydrogen storage, a higher operating voltage), as well as the increase of the plant size, may render this type of energy storage more competitive in remote applications.

At the present time, the complexity and high costs of solar hydrogen systems of this type limit the applicability to isolated locations where high costs for electricity and fuel could create conditions favorable for on-site energy production and storage (e.g. in Antarctic or space bases). Of course, those harsh conditions pose other critical problems for solar-hydrogen plants. In these types of application, energy efficiency of equipment and system often represent a less important point than energy availability and plant reliability.